DASA 1854

AIR-BLAST STUDIES WITH EIGHT SPECIES OF MAMMALS

Donald R. Richmond, Edward G. Damon, I. Gerald Bowen,
E. Royce Fletcher, and Clayton S. White

Technical Progress Report
on
Contract No. DA-49-146-XZ-372

This work, an aspect of investigations dealing with the Biological Effects of Blast from Bombs, was supported by the Defense Atomic Support Agency of the Department of Defense.

Lovelace Foundation for Medical Education and Research
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FOREWORD

This report, in the field of Blast and Shock Biology, presents (1) the pressure-duration relationship and lethality for dogs and goats, (2) threshold lung injury study for dogs, and (3) lethality curves for six small mammalian species compiled with "long"-duration blast waves.

Although the results do not provide final answers in some areas, they are of immediate importance in the medical field and to weapons-effects analysts. Specifically, the response data apply only to exposure against a reflecting surface; however, with appropriate adjustments, they may apply to other conditions of exposure.

Continuing work in this field will facilitate the formulation of better estimates of man's tolerance to air blast, treatment of blast injuries, and development of protective principles.

ABSTRACT

A series of three experiments were carried out. (1) A total of 204 dogs and 115 goats were exposed to shock-tube and high-explosive-produced reflected shock waves ranging in duration from 400 to 1.5 msec. LD_{50} values, calculated by probit analysis, showed similar patterns for both species, increasing at the shorter durations by a factor of 4 or 5 above those for long durations. (2) Sixty dogs were exposed in a shock tube to "sharp"-rising overpressures of near 400-msec duration at six-dose levels ranging from 9.2 to 35.8 psi. The degree of lung injury was graded and threshold for petechial hemorrhage determined. (3) Dose-response curves were compiled using data for 200 mice, 110 hamsters, 150 rats, 120 guinea pigs, 48 cats, and 40 rabbits exposed to "long"-duration reflected pressures in a shock tube. The tolerances (LD_{50}) for all six species are compared. Pathological observations for all species and lung-weight data for cats and hamsters are included.

Criteria for relating biological response to the various parameters of the blast wave are discussed.

ACKNOWLEDGMENTS

The valuable technical assistance of Mr. Charles S. Gaylord, Mr. Peter A. Betz, Mr. Donald E. Pratt, Mr. William Hicks, Mr. Dennis D. Branch, Mr. Kabby Mitchell, Jr., Mr. Keith G. Saunders, Mr. Raymond T. Sanchez, and Mr. Richard Q. Lee during the course of this work is acknowledged.

The authors are indebted to Dr. Thomas L. Chiffelle for guidance in the area of pathology, for help in describing both gross and microscopic findings, and for assessing the significance of blast-induced lesions, particularly in the case of the lung.

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AIR-BLAST STUDIES WITH EIGHT SPECIES OF MAMMALS

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INTRODUCTION

Two of the major problems in the biomedical effects of blast and shock area are (1) the precise relationship between the physical components of the air-blast wave and biological response, and (2) how blast injuries, both anatomical and physiological, affect man's general behavior and work performance.

The first problem has received more attention by far. Although some usable criteria have been set forth, such as peak pressure, side-on pressure impulse, reflected pressure impulse, and pressure duration, none of these generally fit well with the results observed; not even in the apparently simple situation of exposure in the open. Furthermore, existing estimates of man's tolerance to blast are tentative. They were obtained by the extrapolation of data from only five species of mammals using surface area (body weight $^{2/3}$) or body weight as biological parameters.[1, 2, 3] Before more refined estimates of man's tolerance can be made, the response data of additional species should be obtained to make available a wider range of biological parameters for analysis

In regard to the second problem, systematic investigations on the behavioral responses to blast are lacking, except those concerned with hearing alterations produced by high noise levels.[4, 5, 6] In order to proceed in this problem area, the threshold for the various blast injuries must be learned.

The objectives of these studies were (1) to determine the median lethal pressures for "fast"-rising overpressures as functions of duration (LD_{50}'s) for dogs and goats; (2) to relate the degree of lung injury in dogs to graded levels of sublethal blast for determining threshold for lung injury; and (3) to compile dose-response curves with "long"-duration blast waves for small animal species including mice, hamsters, rats, guinea pigs, cats, and rabbits.

METHODS

General

A list of individual experiments with the number of animals used and their body weights (mean and range) is given in Table 1. Both sexes were used in all groups.

In all tests, the animals were mounted against a reflecting surface either left-side-on against the endplate of a shock tube or prone on a concrete pad with the charge detonated directly overhead. Consequently, the peak pressure, or dose, was always taken as the pressure in the reflected shock front.

TABLE I

LIST OF EXPERIMENTS AND ANIMALS USED

	Experiment	Number of Animals*	Body Weight**
I	Response for:		
	Dogs (mongrel)	204	16.5 kg (11.4-25.4)
	Goats (mixed breed)	115	21.9 kg (16.1-29.5)
II	Threshold Lung Injury:		
	Dogs (mongrel)	60	15.7 kg (11.4-22.3)
III	Response of Small Animals:		
	Mice (Webster strain)	200	20.7 g (13-28)
	Hamsters (Mesocricetus auratus)	110	89 g (71-114)
	Rats (Sprague-Dawley)	150	200 g (134-267)
	Guinea Pigs (English short-hair)	120	424 g (352-544)
	Cats (mixed breed)	48	2.48 kg (1.3-4.1)
	Rabbits (New Zealand White)	40	3.70 kg (3.1-4.7)

* Both sexes in all groups.
** Mean and range.

Shock Tubes

Diagrams of the shock-tube configurations employed along with representative pressure-time patterns generated by each are shown in Figures 1 and 2. Each configuration consisted of a compression chamber separated by a plastic diaphragm (Du Pont Mylar®). The compression chamber was air-pressurized to a predetermined level and the diaphragm ruptured to generate a shock wave in the expansion chamber. Since all chambers were open to the outside (vented or gapped), the air inside was initially at one atmosphere absolute pressure (12.0 psia). The expansion chambers were closed distally with a steel plate (endplate) against which the animals were mounted. Incident shock waves reflecting from this endplate subjected the specimens to "sharp"-rising reflected pressures.

In the dog tests, starting with arrangement A" already described,[2] which produced a "sharp"-rising pressure pulse of 300-400-msec duration, the tube configuration was modified by shortening the compression and expansion chambers and introducing additional openings in the expansion section to reduce the pressure duration. The duration of the pressures in arrangements A", I, and I_2 averaged 400, 79.4, and 53.8 msec, respectively (Figure 1). The flat-top portion of these respective pulses measured 30, 15-16, and 4-5 msec. Arrangements J, K, and L produced pulses of 33.6-, 20.9-, and 14.8-msec durations with flat-top durations of 1.3-2.5, 1.0-1.1, and 0.8-0.9 msec, respectively (Figure 2).

Goats were exposed in tube configurations A", I_2, K, and L with additional modifications to I_2, K, and L that produced pressure durations of 62.0, 38.8, and 17.0 msec, respectively.

High-Explosive Charges

High-explosive charges were detonated singly over the center of a 30 x 30-ft, 6-in. reinforced concrete pad previously described.[7]

Charges consisted of bare 64- and 8-lb cast TNT spheres (13 and 6-1/2 in., respectively, in diameter) with spherical 2-oz boosters of Type 9404 PBX at their geometrical centers. Explosives were fired by electric blasting caps (Military J2, Hercules Herco-Tube®) set at the exact center of the charges through a detonator well of 5/16-in. diameter.

Eight 64-lb charges were detonated at 19- to 20-ft burst heights and seventeen 8-lb charges at burst heights of 7 to 9 ft.

Pressure-Time Instrumentation

Details of gauges, gauge mountings, electronic components, and calibration procedures have already been reported.[7] Piezoelectric gauges were used throughout these experiments for pressure-time measurements. In the shock tubes, gauges with quartz crystals (Kistler Model 401) and sensors of lead metaniobate (Susquehanna Model ST-2) were mounted in the walls of the tubes. On each test, at least one gauge was mounted side-on 3 in. upstream of the endplate and one face-on in the endplate. Pencil gauges (Atlantic Research Model LC-33) having sensors of lead zirconate were used to measure pressures from the high explosives. The sensing elements of these gauges were always 0.75 in. above the surface of the concrete pad.

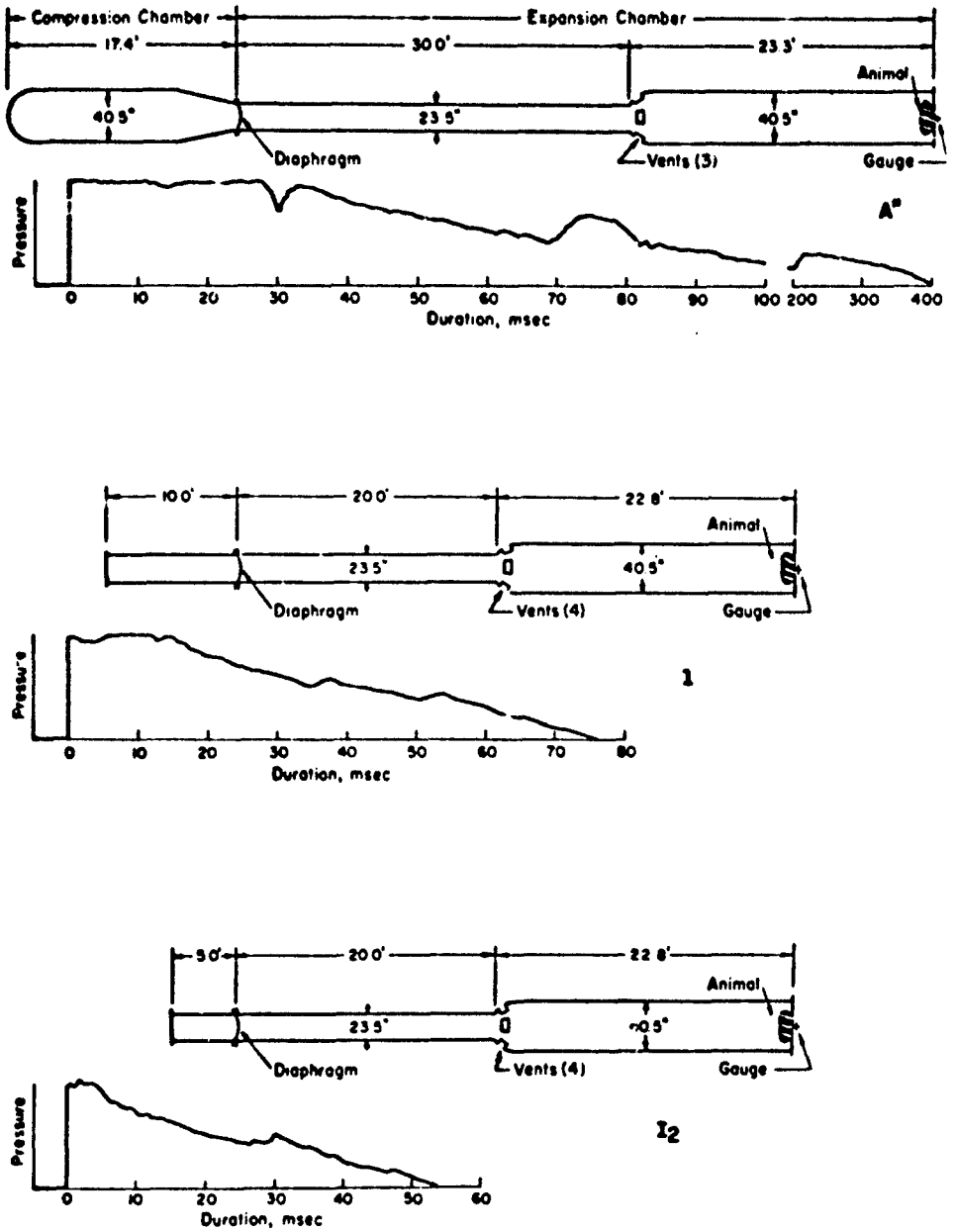

Figure 1. Pressure-Time Recorded in Various Shock-Tube Arrangements.

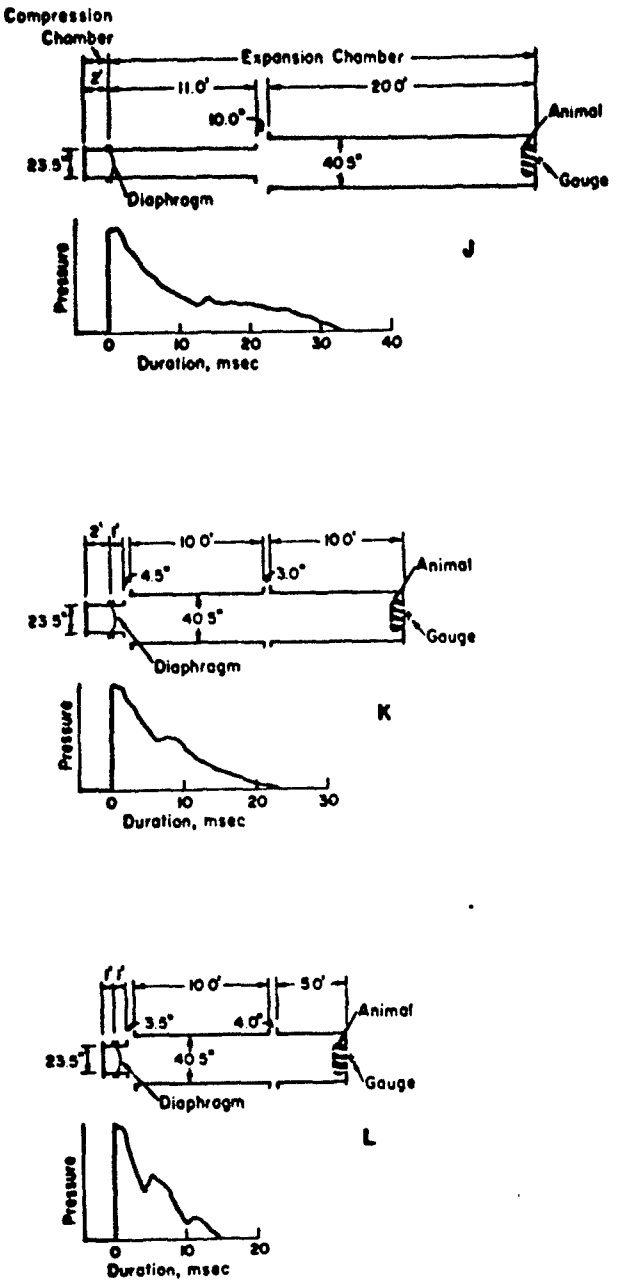

Figure 2. Pressure-Time Recorded in Various Shock-Tube Arrangements.

Experiment I – Response for Dogs and Goats

Using the shock-tube configurations just described, dogs were exposed to air blasts ranging in duration from 400 to 15 msec. Animals were tested, one at a time, mounted in harnesses side-on against the endplate with their right sides facing the incident shock wave.

For high-explosive tests, the animals were exposed to reflected blast waves of 4.6- to 1.5-msec durations that were generated from charges detonated overhead. In these tests, specimens were harnessed and mounted prone on the concrete pad. They were always in the region of regular reflection. The weight-of-charge and height-of-burst determined the number of specimens exposed per shot. Five to six animals were exposed with the 64-lb charges and only two or three on the 8-lb firings.

Except for seven dogs that died unobserved during the night, those killed by the blast were autopsied within 10-15 minutes after death. Of the survivors, six tested in shock-tube J were serially sacrificed, one each on days 3, 7, 14, 21, 31, and 60. Most of the remaining survivors were sacrificed at 24 hours by intravenous injections of sodium pentabarbital, exsanguinated, and then autopsied.

The experimental procedures for goats paralleled those for the dogs, except for the few modifications in the shock tubes. In addition, 12 survivors from shock-tube K were observed for 30 days.

Experiment II – Threshold Lung Injury in Dogs

Shock-tube configuration A" was used to expose mongrel dogs to reflected overpressures of 320-348-msec duration. Groups of 10 animals were individually exposed to six dose levels ranging between 9.2 and 35.8 msec. The methods of exposure were identical to those for dogs in Experiment I.

In these tests, the animals were sacrificed and autopsied one hour post-shot. All gross lung injuries were recorded and the lungs were weighed, photographed, and portions taken for histological study.

Heart and respiratory rates were recorded pre-shot, post-shot, and at 10-minute intervals for one hour. The heart rate was measured by the pulse and electrocardiograph (Sanborn Model 62) and the respiratory rate by excursions of the chest wall.

Experiment III – Response of Small Animals

Groups of small animals comprised of mice, hamsters, rats, guinea pigs, cats, and rabbits were exposed, by types, in shock-tube arrangement A" to graded pressure levels with durations of 329-380 msec.

Animals were mounted against the endplate of the shock tube, right-side-on to the incident wave in semi-cylindrical cages constructed of wire mesh or expanded metal with the curved surface outward. These cages had maximal open areas of approximately 90 per cent so they would not offer protection against the blast wave. Cages were sized to fit the specimens being exposed to hold them side-on. Ten of the smaller animals and two cats or rabbits were exposed per test.

All animals killed by the blast were autopsied 10 or 15 minutes after death. With few exceptions, survivors were sacrificed within 24 hours

with either Nembutal or chloroform, exsanguinated, and then autopsied.

RESULTS

Response for Dogs and Goats – Experiment I

Lethality

The fraction of dogs and goats that died within 24 hours from each pressure source, in relation to the reflected pressure levels and durations, is given in Tables 2 and 3. The results of the probit analysis of these data are summarized in Tables 4 and 5 to show the LD_{50}-24-hour reflected pressures at various durations.[8] In several instances, the LD_{50} was calculated from one datum point.[7] Constants for the probit regression equation adjusted to an average slope are included. The 50-per cent lethality points, as related to duration, are plotted in Figure 3. Included in the graph are iso-impulse lines for reflected pressure computed from the measured peak pressures and durations, using equations developed at BRL,[9] and scaled to an ambient pressure of 12 psia.

The constant lethality curves plotted in Figure 3 are similar for both animals with the tolerance of the goats slightly higher than the dogs.

Of the 12 goat survivors from shock-tube K, three expired on day 2 and one on day 3. There were no additional deaths between 3 and 30 days.

Pathological Findings

The pathological findings for both specimens followed a definite pattern reviewed before; namely, pulmonary hemorrhage with bloody froth at the nose and mouth, air embolism, disruption of the tissues lining portions of the gastrointestinal tract, sinus hemorrhage, and eardrum rupture.[10] There was an occasional ruptured liver or spleen, or both, at the higher dose levels. A few of the results should be emphasized.

First, neither the severity of the lung damage (judged visually or based on lung weight) nor the incidence of coronary air emboli varied importantly with pressure duration in fatalities (Figures 4, 5, and 6). That is to say, at LD_{50} levels the nature and severity of blast lesions did not change significantly over the range of durations studied. Based on one-hour lethality in dogs, there was 81-per cent incidence of coronary air embolism from the shock-tube pressure sources and 84 per cent from high explosives. Comparable figures for goats were 71 per cent and 73 per cent.

Second, the lung weights of the survivors were less than those of the nonsurvivors (Figures 4 and 5).

Third, air emboli were not always limited to the arterial side of the circulatory system as previously supposed, but were found in the venous side as well. These air or gas bubbles were found in mesenteric, phrenic, intercostal arteries and veins as well as the heart and in the brain. Several of the animals that died beyond 1/2 to 1 hour also sustained air emboli.

TABLE 2

DOG MORTALITY AS RELATED TO PRESSURE-TIME

Pressure Source	Reflected Pressure, psi	Duration, msec	24-Hour Mortality No. Dead / Total	Percent
Shock Tube:				
A"	39.2	400	0/5	0
	44.1		1/10	10.0
	48.1		6/10	60.0
	53.0		9/10	90.0
			LD_{50}= 47.9 psi	
I	42.5	79	1/7	14.3
	47.3		2/6	33.3
	50.7		2/3	66.7
			LD_{50}= 49.5 psi	
I_2	36.2	54	0/4	0
	43.4		1/9	11.1
	48.7		3/7	42.8
	59.4		1/1	100
			LD_{50}= 50.8 psi	
J	46.2	34	4/10	40.0
			LD_{50}= 47.9 psi	
K	38.1	21	1/8	12.5
	40.8		1/5	20.0
	48.8		2/4	50.0
	51.4		4/6	66.7
	54.5		4/5	80.0
			LD_{50}= 47.3 psi	
L	43.4	15	1/9	11.1
	50.0		2/9	22.2
	53.3		5/9	55.6
	59.5		5/9	55.6
			LD_{50}= 54.8 psi	
High Explosives:				
64 lb:				
20' & 21' HOB	73.0	5.0	1/11	9.1
20' HOB	81.9	4.6	2/6	33.3
20' HOB	88.8	4.6	3/6	50.0
20' HOB	95.6	3.9	4/6	66.7
	Mean	4.5	LD_{50}= 88.6 psi	
8 lb:				
8' & 9' HOB	109.0	2.1	1/8	12.5
			LD_{50}= 128.7 psi	
7.5' HOB	201.8	1.7	7/9	77.8
			LD_{50}= 180.6 psi	
7' HOB	240.1	1.5	9/12	75.0
			LD_{50}= 217.7 psi	

TABLE 3

GOAT MORTALITY AS RELATED TO PRESSURE-TIME

Pressure Source	Reflected Pressure, psi	Duration, msec	24-Hour Mortality No. Dead / Total	Percent
Shock Tube:				
A"	44.9	400	2/10	20.0
	51.4		4/10	40.0
	56.9		3/5	60.0
	59.3		4/5	80.0
			LD_{50}= 52.6 psi	
I_2	52.2	62	3/10	30.0
			LD_{50}= 55.9 psi	
K	47.6	40	1/6	16.7
	55.4		4/8	50.0
	58.6		5/7	71.4
	60.8		6/7	85.7
			LD_{50}= 54.3 psi	
L	54.2	17	1/5	20.0
	57.6		2/4	50.0
	62.6		5/6	83.3
	68.2		5/5	100
			LD_{50}= 56.9 psi	
High Explosives:				
64 lb-19' HOB	98.7	4.4	1/5	20.0
	106.1		3/5	60.0
	111.9		3/5	60.0
			LD_{50}= 106.8 psi	
8 lb-7' HOB	256.0	1.5	6/12	50.0
			LD_{50}= 256.0 psi	

TABLE 4

THE LD_{50}-24-HOUR REFLECTED PRESSURES
AT VARIOUS DURATIONS FOR THE DOG

Pressure Source	Number of Animals	LD_{50}, psi	Duration, msec	Adjusted Probit Equation Constants	
				intercept, a	slope, b
Shock Tube:					
A''	35	47.9 (44.8-51.4)	400	-21.680	15.876*
I	16	49.5 (44.9-55.4)	79.4	-21.901	15.876
I_2	21	50.8 (46.2-57.0)	53.8	-22.076	15.876
J**	10	47.9 (42.6-54.3)	33.6	-21.680	15.876
K	28	47.3 (43.5-51.6)	20.9	-21.590	15.876
L	36	54.8 (51.2-59.2)	14.8	-22.605	15.876
High Explosives:					
64 lb	29	88.6 (82.1-96.6)	4.6	-25.916	15.876
8 lb**	8	128.8 (109.6-157.2)	2.1	-28.496	15.876
	9	180.6 (154.3-206.2)	1.7	-30.827	15.876
	12	217.7 (190.4-243.5)	1.5	-32.116	15.876

* Standard error of the slope constant ±2.585.
** Calculated from one datum point.

TABLE 5

THE LD_{50}-24-HOUR REFLECTED PRESSURES
AT VARIOUS DURATIONS FOR THE GOAT

Pressure Source	Number of Animals	LD_{50}, psi	Duration, msec	Adjusted Probit Equation Constants	
				intercept, a	slope, b
Shock Tube:					
A''	30	52.6 (49.0-56.9)	400	-25.087	17.480*
I_2**	10	55.9 (50.2-64.6)	62.0	-25.549	17.480
K	28	54.3 (50.0-58.2)	38.8	-25.330	17.480
L	20	56.9 (51.2-61.7)	17.0	-25.677	17.480
High Explosives:					
64 lb	15	106.8 (97.2-117.9)	4.4	-30.456	17.480
8 lb**	12	256.0 (230.6-284.2)	1.5	-37.095	17.480

* Standard error of the slope constant ±3.983.
** Calculated from one datum point.

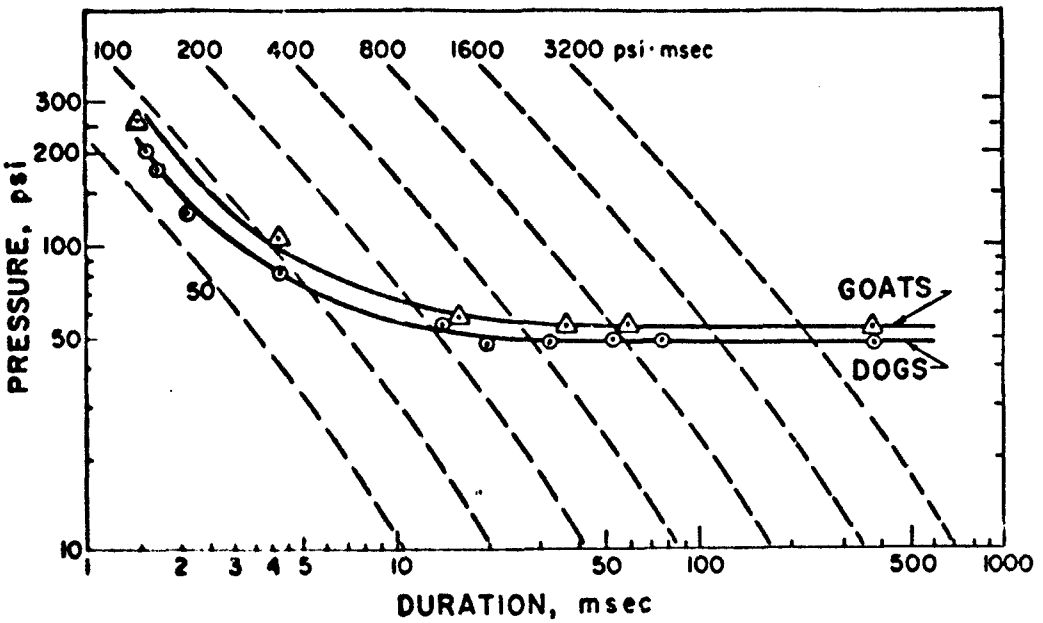

Figure 3. Pressure-Duration Relationship and 50-Per Cent Lethality for Dogs and Goats.

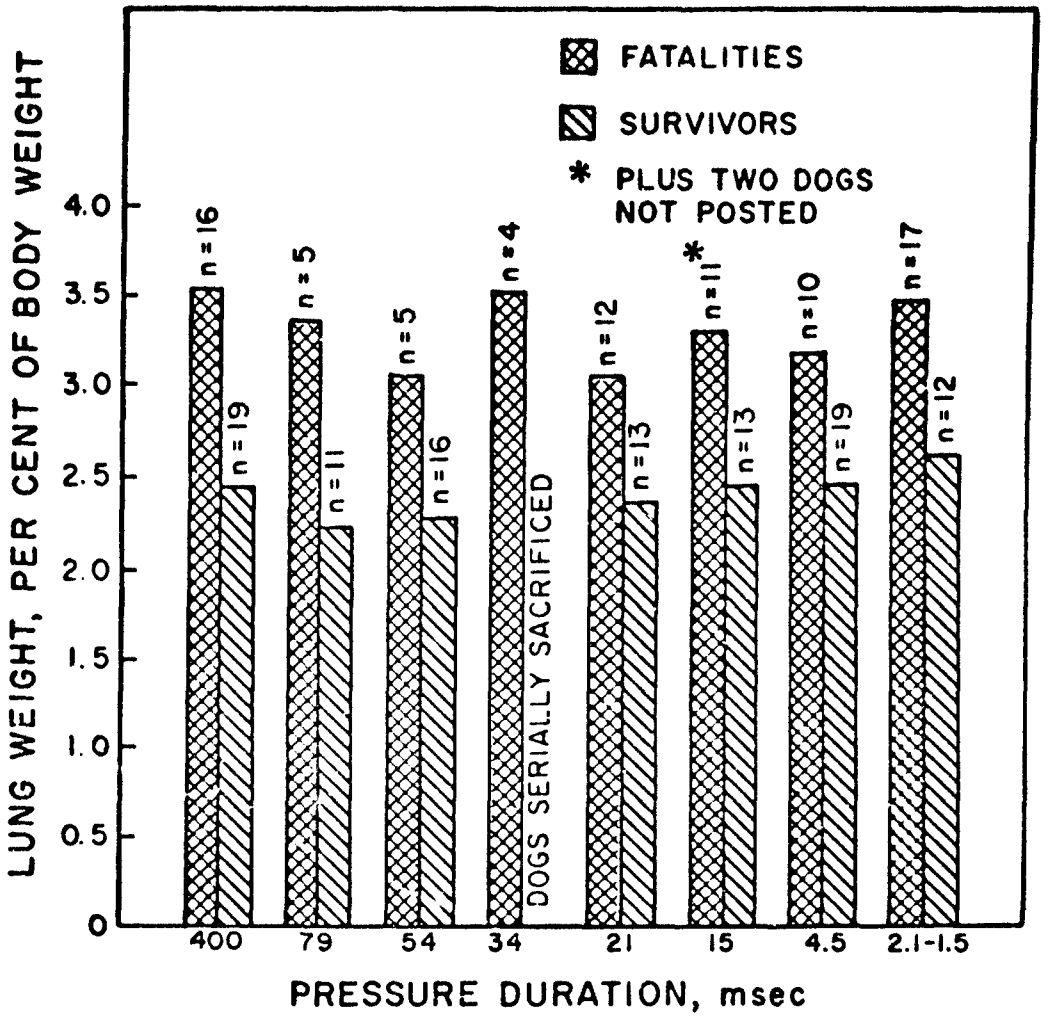

Figure 4. Lung Weights for Dogs Exposed to "Sharp"-Rising Pressures of Various Durations. (See Table 2 for the Pressure Sources Used.)

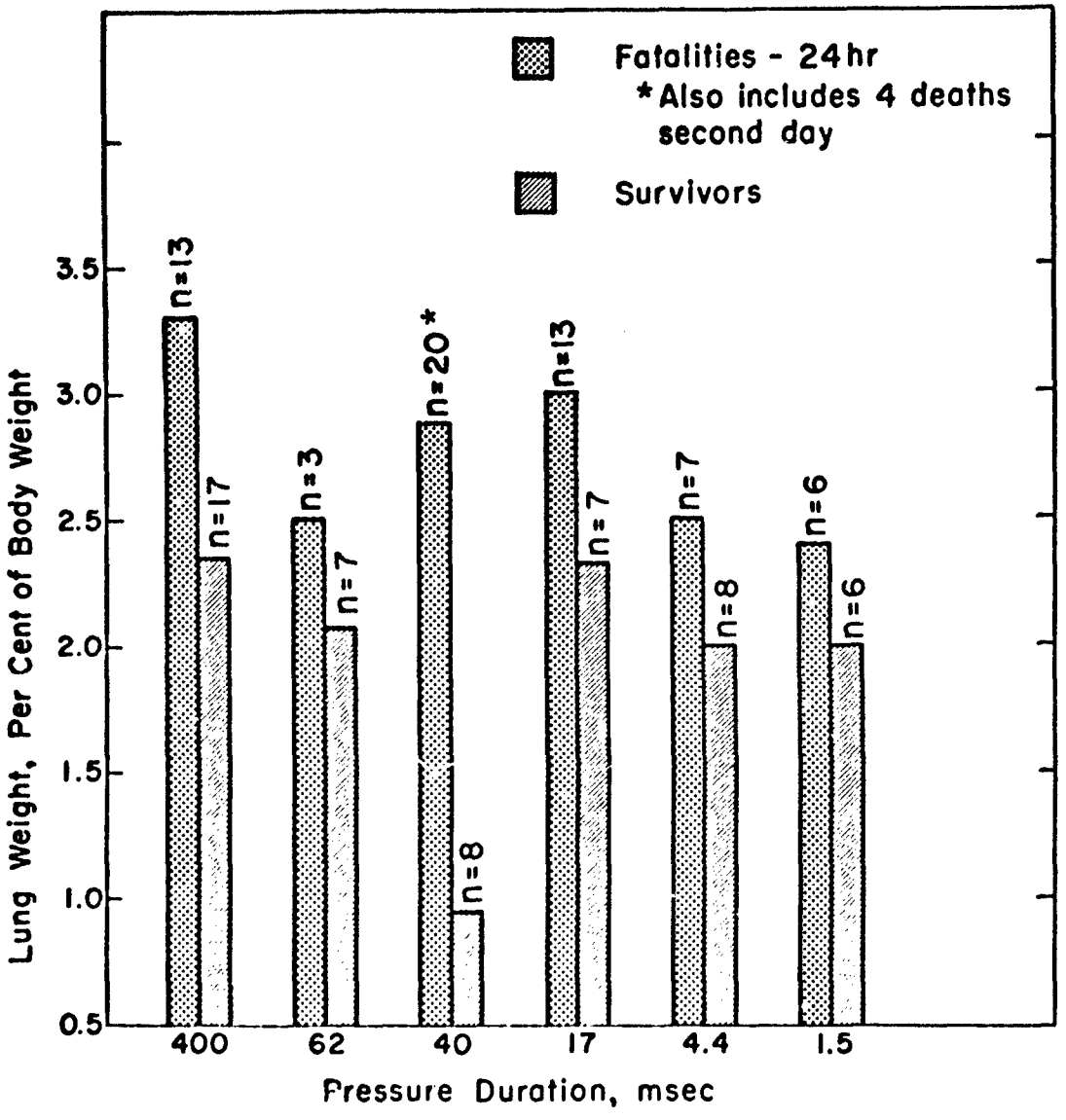

Figure 5. Lung Weights for Goats Exposed to "Sharp"-Rising Pressures of Various Durations. (See Table 3 for the Pressure Sources Used.)

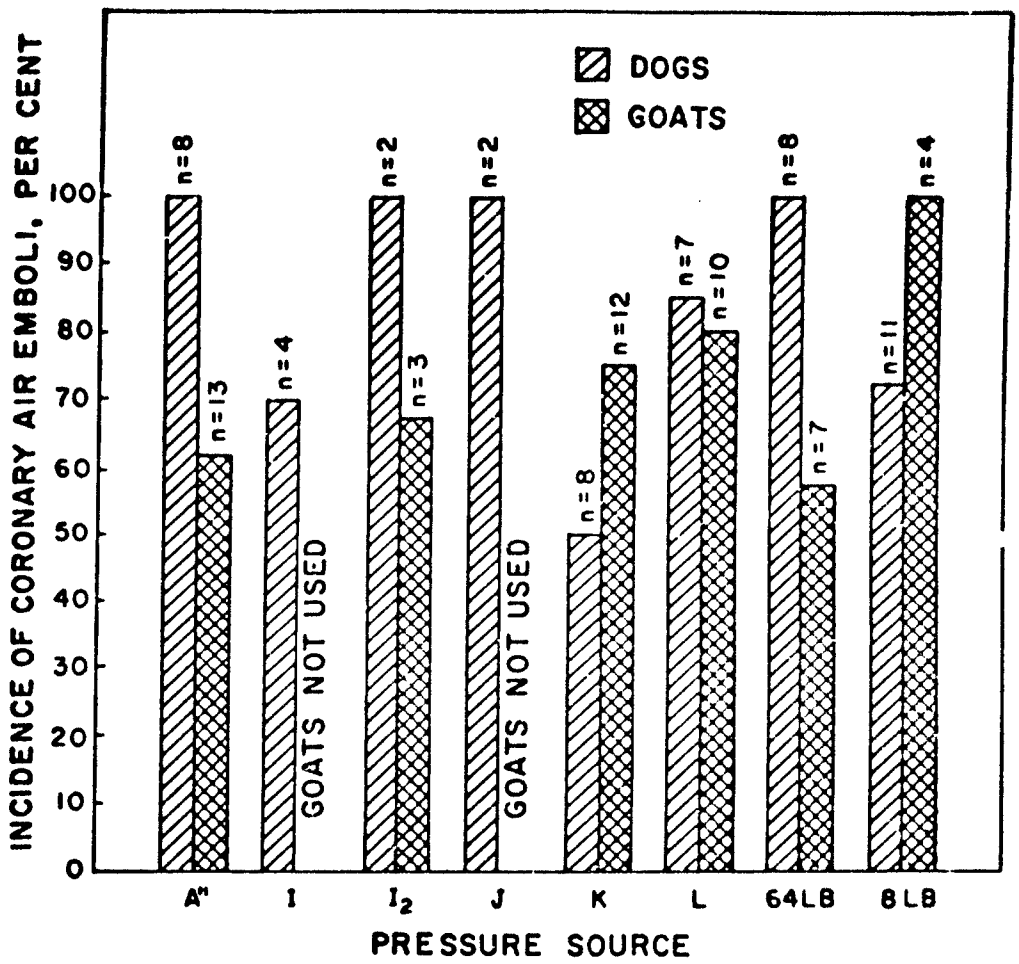

Figure 6 Incidence of Coronary Air Embolism in Dogs and Goats Exposed to "Sharp"-Rising Pressures of Various Durations Produced by Different Pressure Sources. (See Tables 2 and 3 for the Pulse Durations Associated with Each Source.) (One-Hour Mortality)

Fourth, eardrum-rupture data for dogs show that, at LD_{50} pressures, eardrum rupture ranged between 86 and 100 per cent. No duration effect could be detected.

Animals Sacrificed After 24 Hours

The results of the pathological findings for serially sacrificed dogs will be included in a future report dealing with the effects of cortisone, combiotic, and papase on lung injuries.

Eight goats that survived from shock-tube K were sacrificed at 30 days. Based on results from the other groups, these animals undoubtedly had extensive pulmonary hemorrhage and perforated eardrums; however, at autopsy, their lung weights were in the control range (average, 0.89 per cent) and appeared normal except for remnants of hemoglobin pigment – hemosiderin. All but 5 of the 16 eardrums were intact, indicating an apparent healing during this time period.*

Threshold Lung Injury in Dogs – Experiment II

The mean incident and reflected pressures for the six pressure ranges to which dogs were exposed along with the degree of lung injury are given in Table 6. The pulmonary hemorrhages were arbitrarily separated into four categories: (1) petechial hemorrhages; (2) small, isolated hemorrhages 1-2 in. in diameter; (3) confluent hemorrhages which were consolidations of the isolated areas; and (4) entire lobes when nearly all the area of a particular lobe was involved – the latter were only encountered in the lethality study. Typical lungs from these tests, ranging from no damage to confluent hemorrhage, are shown in Figures 7 and 8.

In test range I, which received reflected pressures of 8.5-10 psi, no lung damage was detected. In the second range, with reflected pressures of 11.7-16.2 psi, 6 of 10 dogs sustained petechial lung hemorrhages and 4 were negative. In range III, exposed to a mean pressure of 19.9 psi, 8 of the animals had small, isolated hemorrhagic areas of 1-2 square inches. The remaining 2 animals had little more than petechial hemorrhages except for hyperemia and ecchymotic areas. In the three remaining ranges, the degree of lung hemorrhage rose from 10 cases having isolated areas (range IV) to 8 with confluent hemorrhages in range VI. There was one fatality in the higher pressure ranges.

The portion of the lung in which petechial hemorrhage first appeared was along the posterior (parietal) surface of the diaphragmatic lobes in the form of rib markings and on the visceral (ventral) surface of the cardiac fossa. These same portions of the lungs are usually the site of more severe lung injury in animals subjected to higher pressure levels.

A comparison of the lung weight, in terms of per-cent body weight at each pressure dose, is shown in Figure 9. Included in the figure are

---

*Since the experiments reported above were completed, renal and cardiac infarcts have been found in cattle and sheep sacrificed 30 days after exposure to blast. They have not yet been noted in dogs, goats or other animals surviving blast, but probably will be.

TABLE 6

INCIDENCE AND DEGREE OF LUNG HEMORRHAGE AND EARDRUM RUPTURE IN DOGS

Group	Pressure, psi: Incident Shock	Pressure, psi: Reflected Shock[a]	Lung Weight Percent Body Weight	Remarks	Eardrum Rupture
I	3.7	9.2 (8.5-10.0)	0.86±0.04[b] (0.68-1.14)	No lung hemorrhage present.	2/20[c] (10%)
II	5.6	13.5 (11.7-16.2)	0.84±0.04 (0.67-1.10)	4 cases with no lung hemorrhage, 6 with petechia.	18/20 (90%)
III	7.6	19.9 (19.3-21.0)	0.94±0.05 (0.68-1.16)	2 cases of lungs with petechia, 8 with small isolated areas of hemorrhage.	14/20 (70%)
IV	9.5	25.6 (25.0-26.7)	0.98±0.03 (0.84-1.13)	10 cases of lungs with small isolated areas of hemorrhage.	20/20 (100%)
V	10.8	31.2 (30.3-32.5)	1.19±0.08 (0.86-1.67)	3 cases of lungs with small isolated areas and 7 with confluent hemorrhages.	20/20 (100%)
VI	12.4	35.8 (33.8-38.6)	1.28±0.11 (0.82-2.10)	2 cases of lungs with small isolated areas and 8 with confluent hemorrhages.	19/20 (95%)

[a] Pressure durations: 320-348 msec.
[b] Mean, standard error of the mean, and range.
[c] Number ruptured over the number exposed.

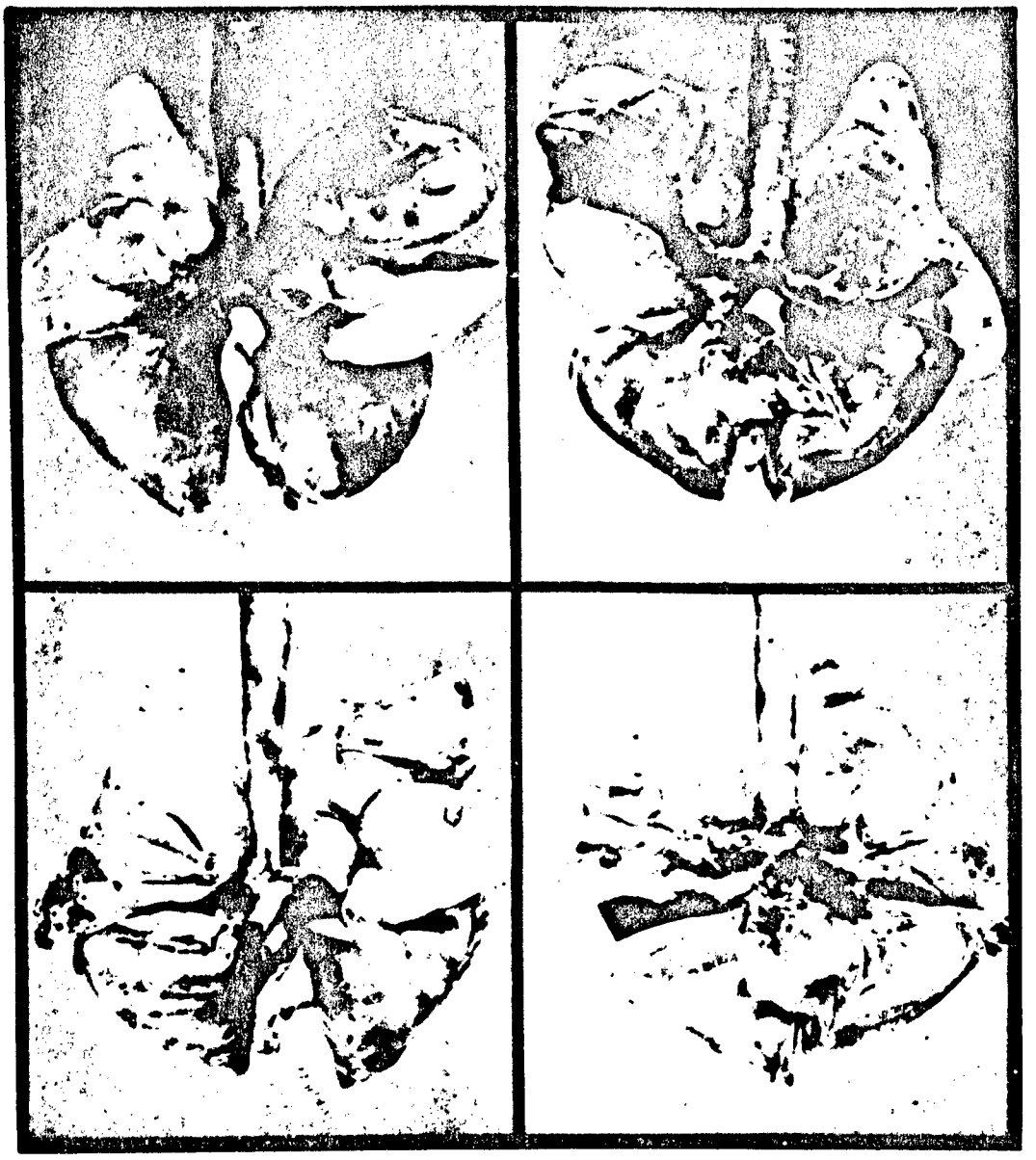

Figure 7. Lungs of Air-Blasted Dogs Showing No Hemorrhage (upper) and Petechial Hemorrhage (lower).

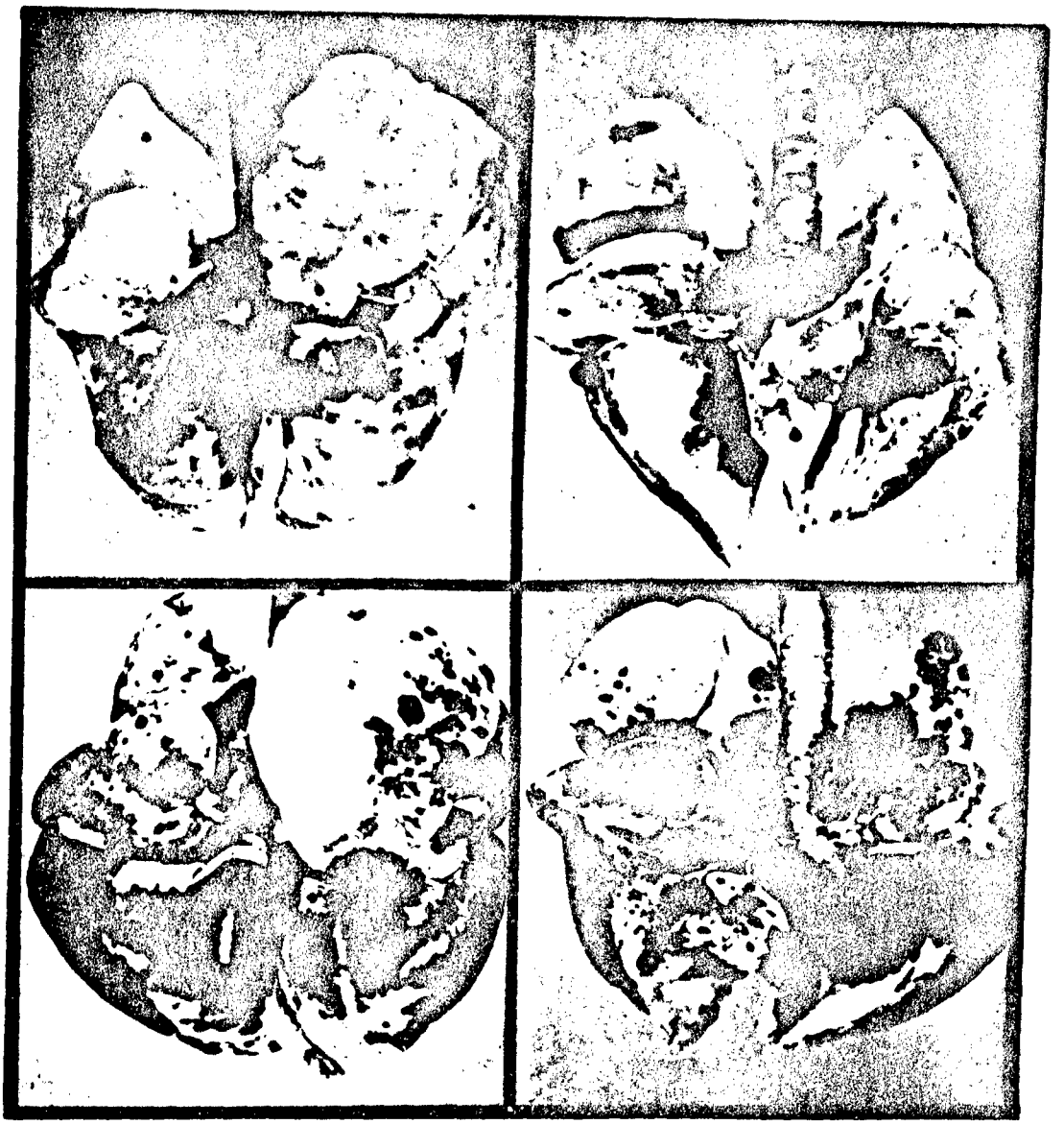

Figure 8. Lungs of Air-Blasted Dogs Showing Isolated Hemorrhage (upper) and Confluent Hemorrhage (lower).

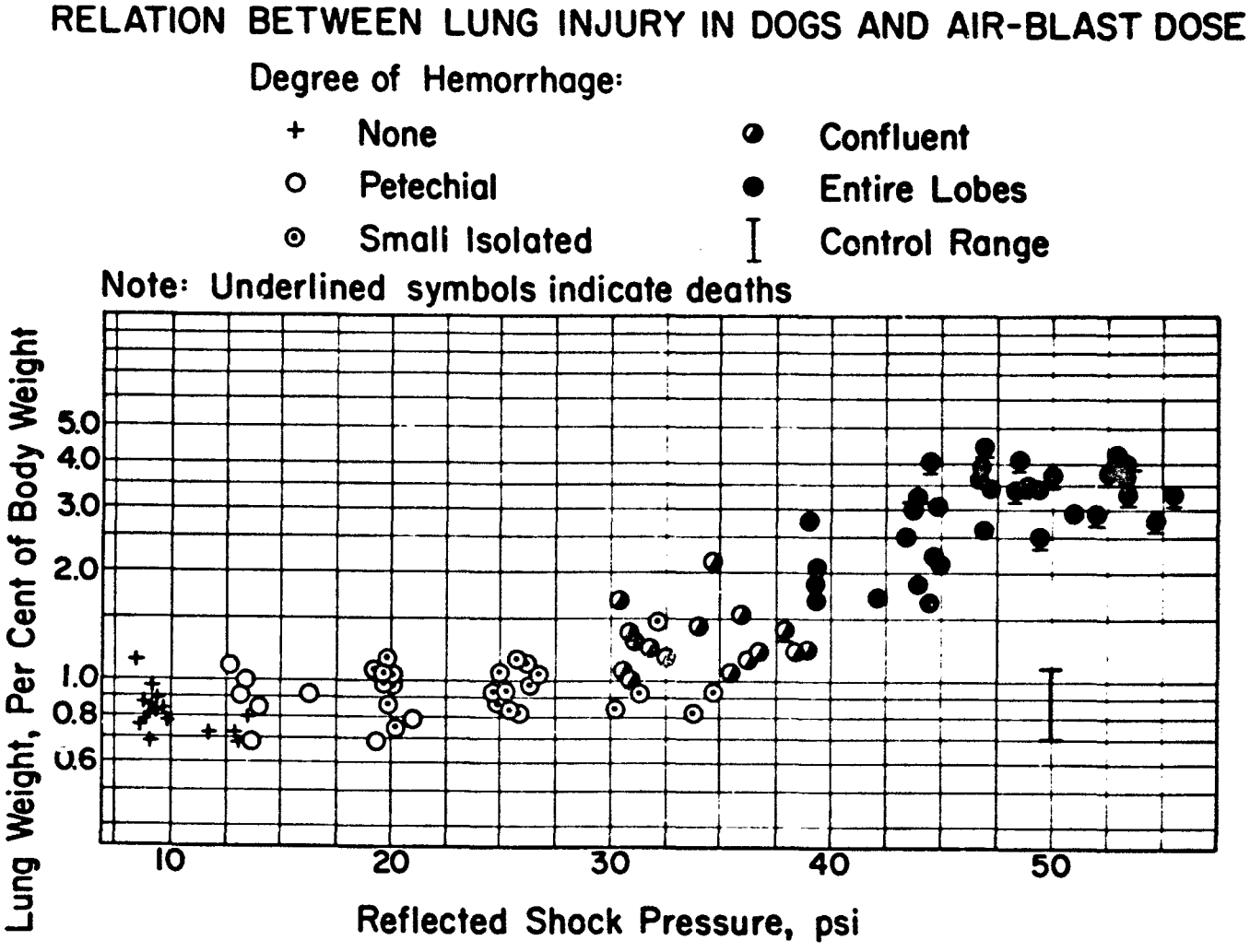
RELATION BETWEEN LUNG INJURY IN DOGS AND AIR-BLAST DOSE
Degree of Hemorrhage:
+ None
Confluent
Petechial
Entire Lobes
Small Isolated
Control Range
Note: Underlined symbols indicate deaths
Lung Weight, Per Cent of Body Weight
5.0
4.0
3.0
2.0
1.0
0.8
0.6
10
20
30
40
50
Reflected Shock Pressure, psi

Figure 9

the lung-weight data from dogs exposed to pressure in the lethal range in that part of Experiment I involving shock-tube configuration A". It can be seen from Figure 9 that the lung weight does not increase importantly until range V, which received 30.3-32.5 psi. The mean for this range (31.2) was statistically higher than the four ranges that received lower pressures.

The lung hemorrhages observed grossly were microscopically verified. At the range I level, emphysematous changes were noted microscopically in the experimental animals, but similar findings were also seen in the control group and no difference between them could be established. However, emphysema was definitely more marked in experimental animals exhibiting hemorrhages 0.5 cm or greater in diameter; viz., in the pressure range III animals and in a few in pressure range II.*

Disruption of the alveolar septa was routinely found in and adjacent to hemorrhagic areas. Peribronchial clefting (two cases) was first noted in range II. Peribronchial and perivascular clefting was recorded in the majority of the tissue samples from dogs in ranges III-VI. Stripping of the bronchial epithelium was commonly observed in lung tissue beginning in range III.

Respiratory and Heart Rates

Figures 10 and 11 give the heart and respiratory rates of four animals that are more or less representative of the average for their respective ranges. Although the variations encountered were considerable, the following general remarks apply. At the two lowest pressure levels (ranges I and II), the respiratory rate and heart rate remained unchanged (Figure 10, dogs 392 and 387). In ranges III and IV, the respiratory rates nearly doubled at about 20-40 minutes following exposure (Figure 11, dog 390). Within these ranges, the pulse rate remained unaffected, although, in some instances, it quickened. At the two highest pressure levels, where the majority had confluent hemorrhage, the respiratory rates rose immediately after exposure, breathing was rapid and shallow, and there was a possible slowing of the heart (Figure 11, dog 394).

Eardrum Rupture

The incidence of eardrum rupture as related to pressure level for "long"-duration pulses is shown in Table 6. The high incidence of rupture for all animals, except those at the lowest pressure range, indicates that the effective dose for 50-per cent eardrum rupture under the conditions of this experiment lies between group I (9.2 psi with 10 per cent) and group II (13.5 psi with 90 per cent).

Response of Small Animals – Experiment III

Dose-Response Curves

Probit mortality curves for each species, relating mortality in probit units to the log reflected pressure, are shown in Figures 12-17. Calculated LD_{50} values, 95-per cent confidence limits, and probit equations

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*Appreciation is expressed to Dr. Thomas L. Chiffelle who kindly made the data reported here available.

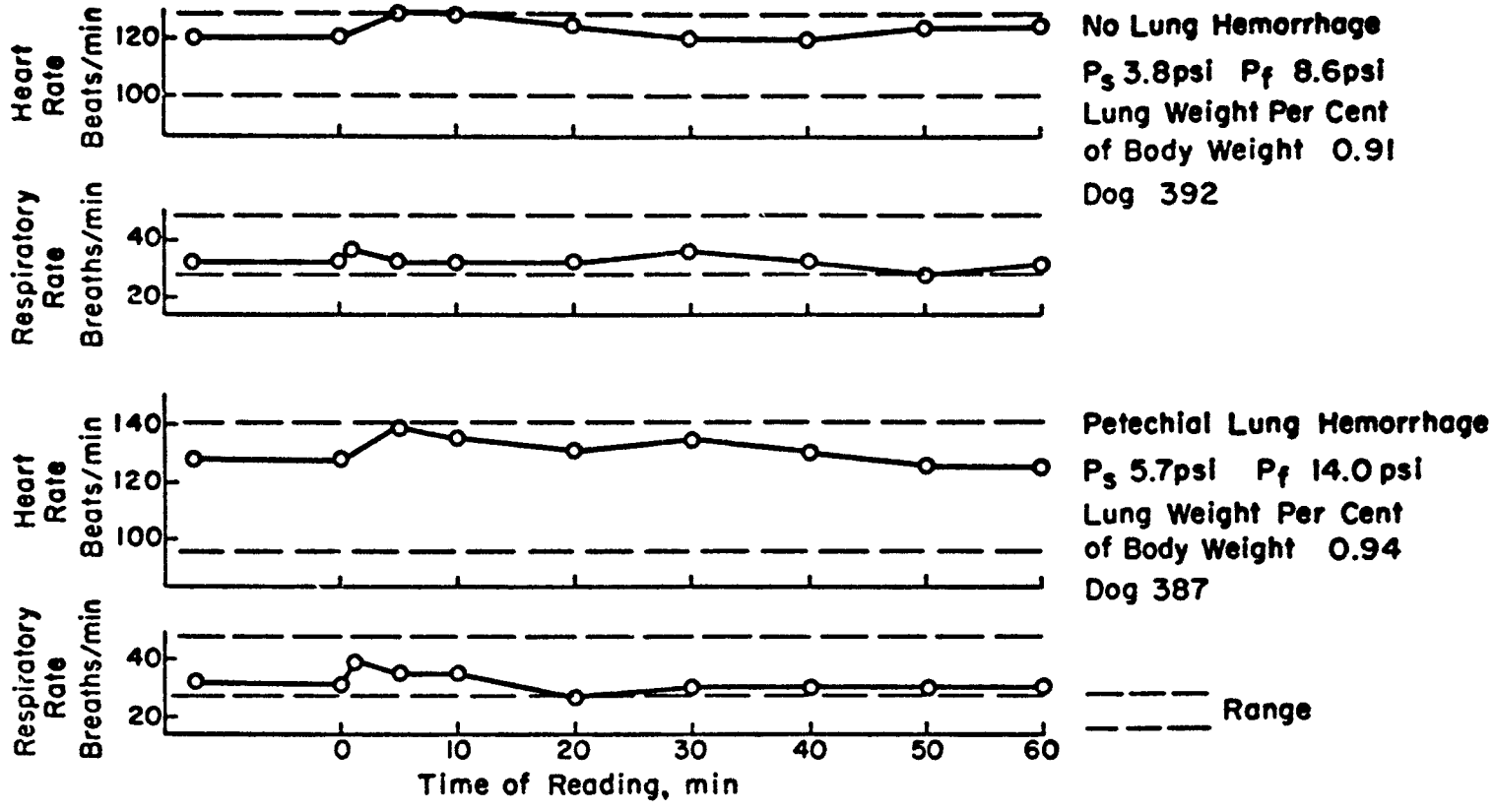

Figure 10. Heart and Respiratory Rates of Dogs with No and Petechial Lung Hemorrhage Compared with Ranges for One Week Pre-Exposure.

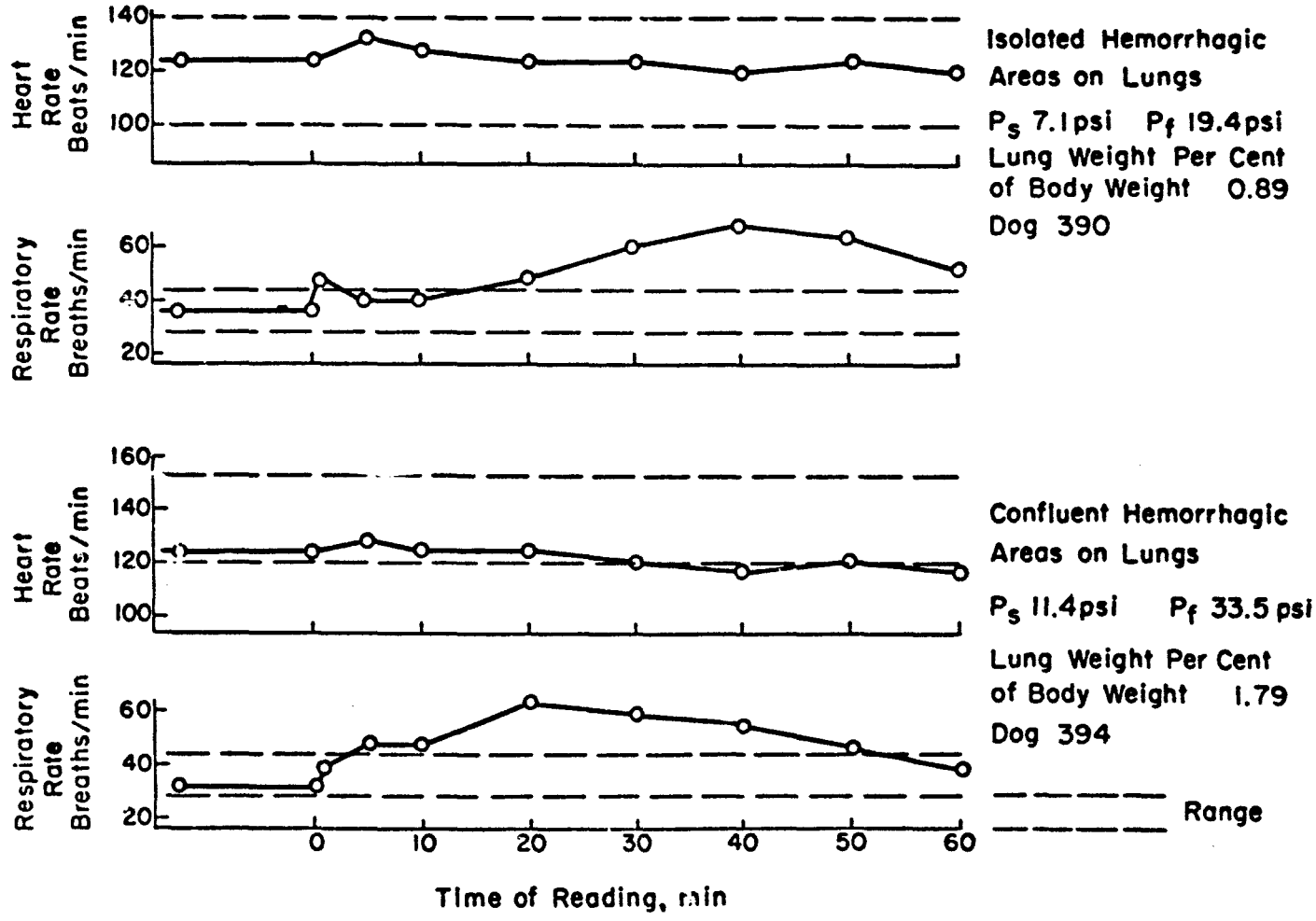

Figure 11. Heart and Respiratory Rates of Air-Blasted Dogs with Isolated and Confluent Lung Hemorrhage Compared with Ranges for One Week Pre-Exposure.

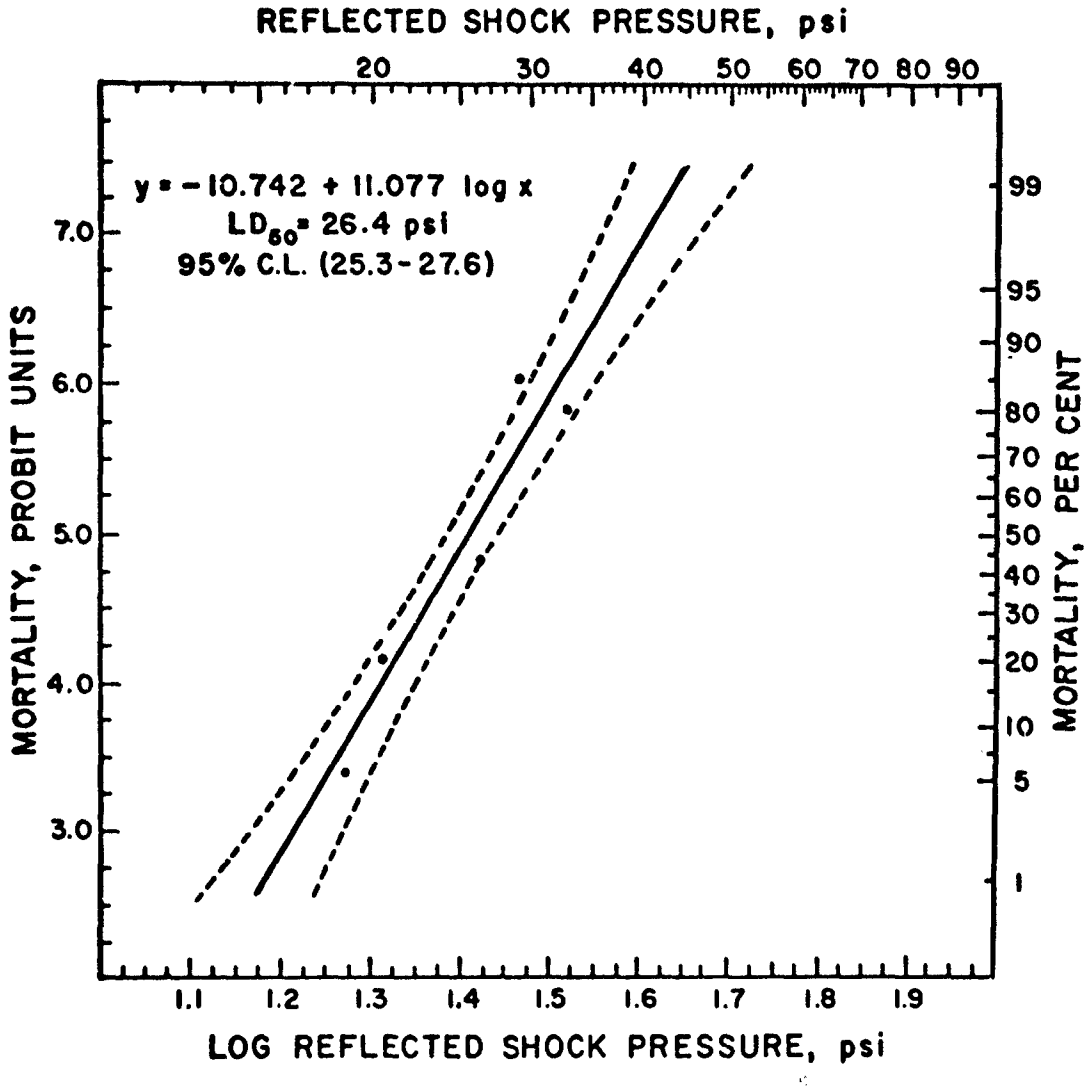

Figure 12. Probit Mortality Curve for Mice Exposed to Reflected Pressures of 329-346-Msec Duration.

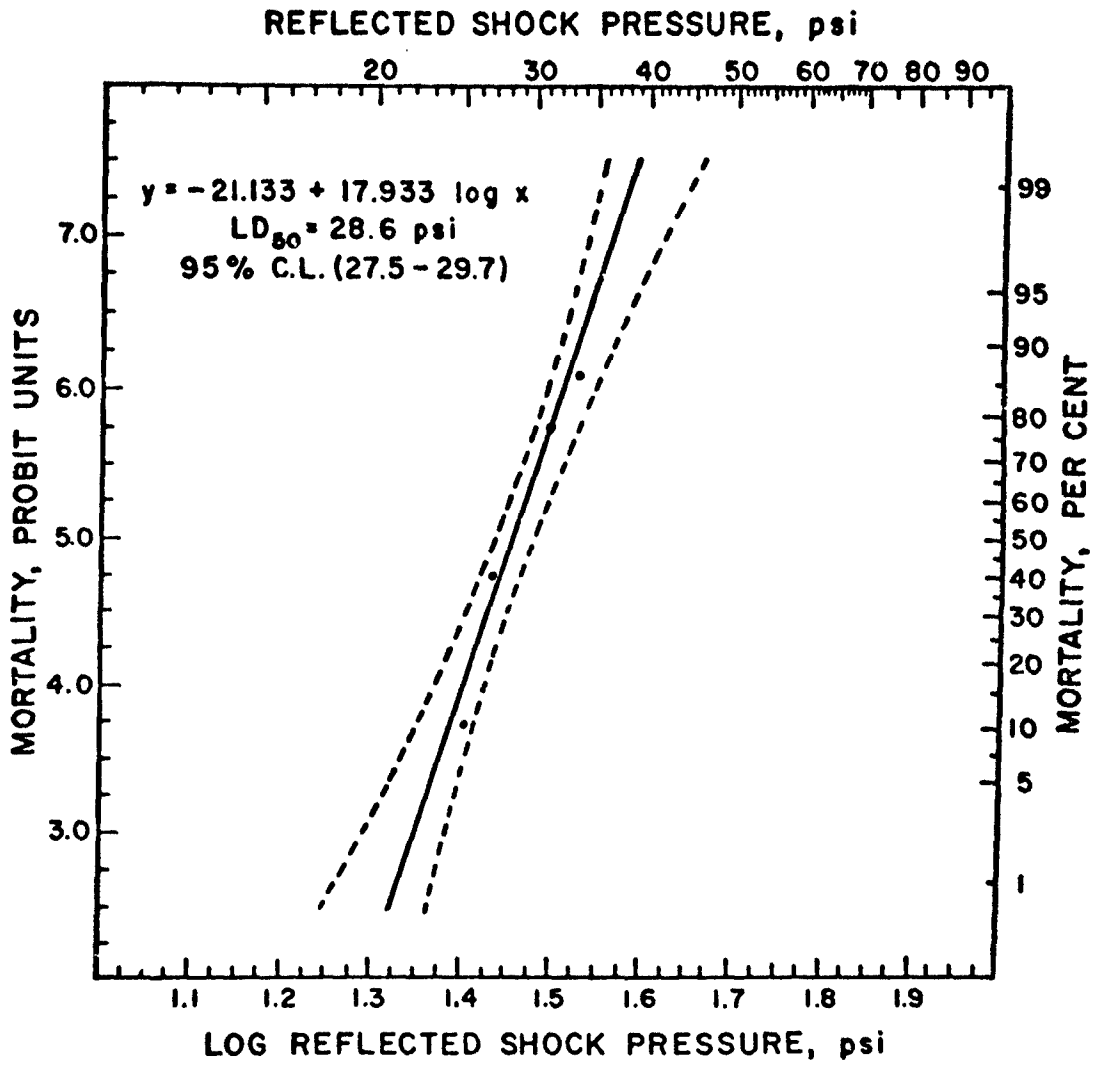

Figure 13. Probit Mortality Curve for Hamsters Exposed to Reflected Pressures of 345-372-Msec Duration.

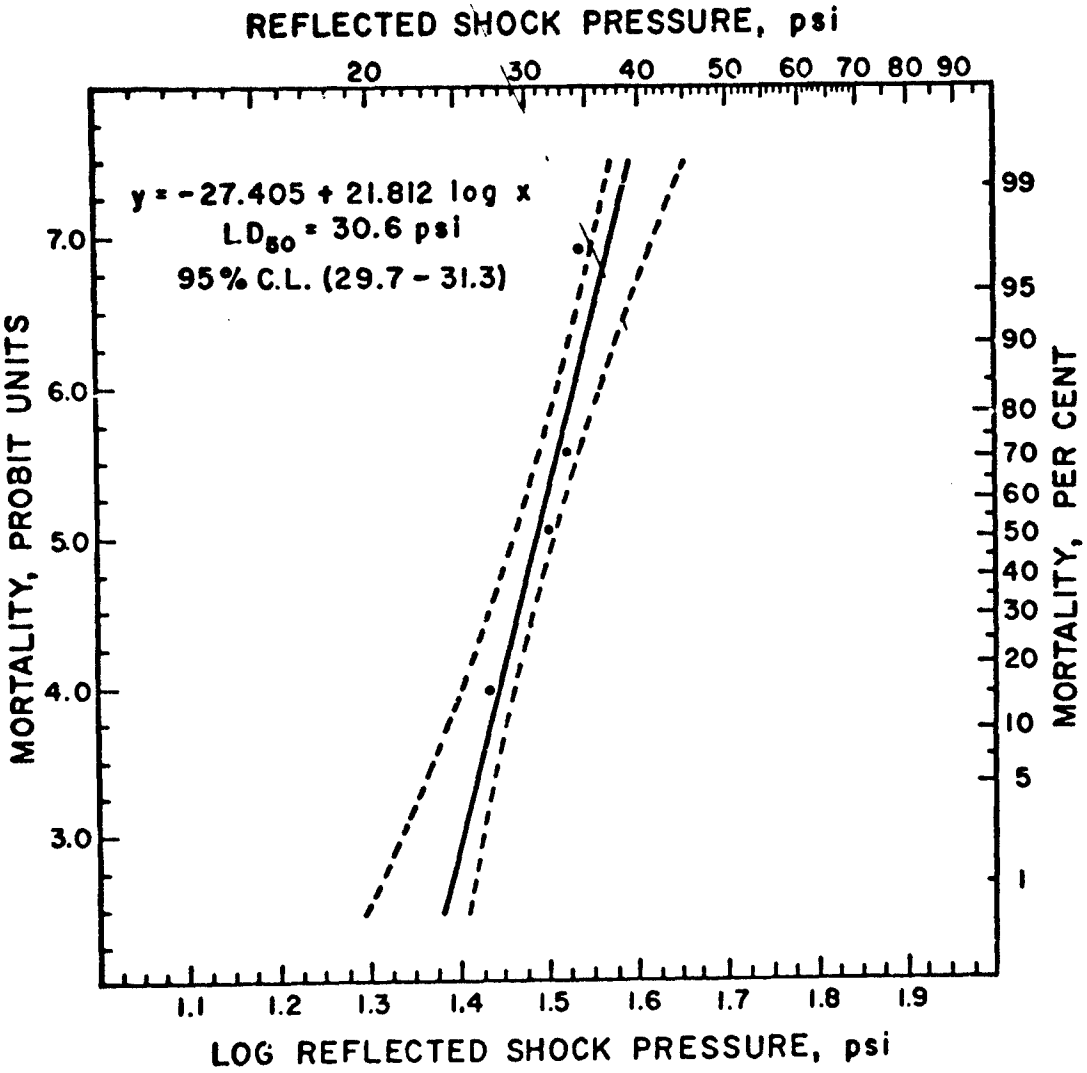

Figure 14. Probit Mortality Curve for Rats Exposed to Reflected Pressures of 332-345-Msec Duration.

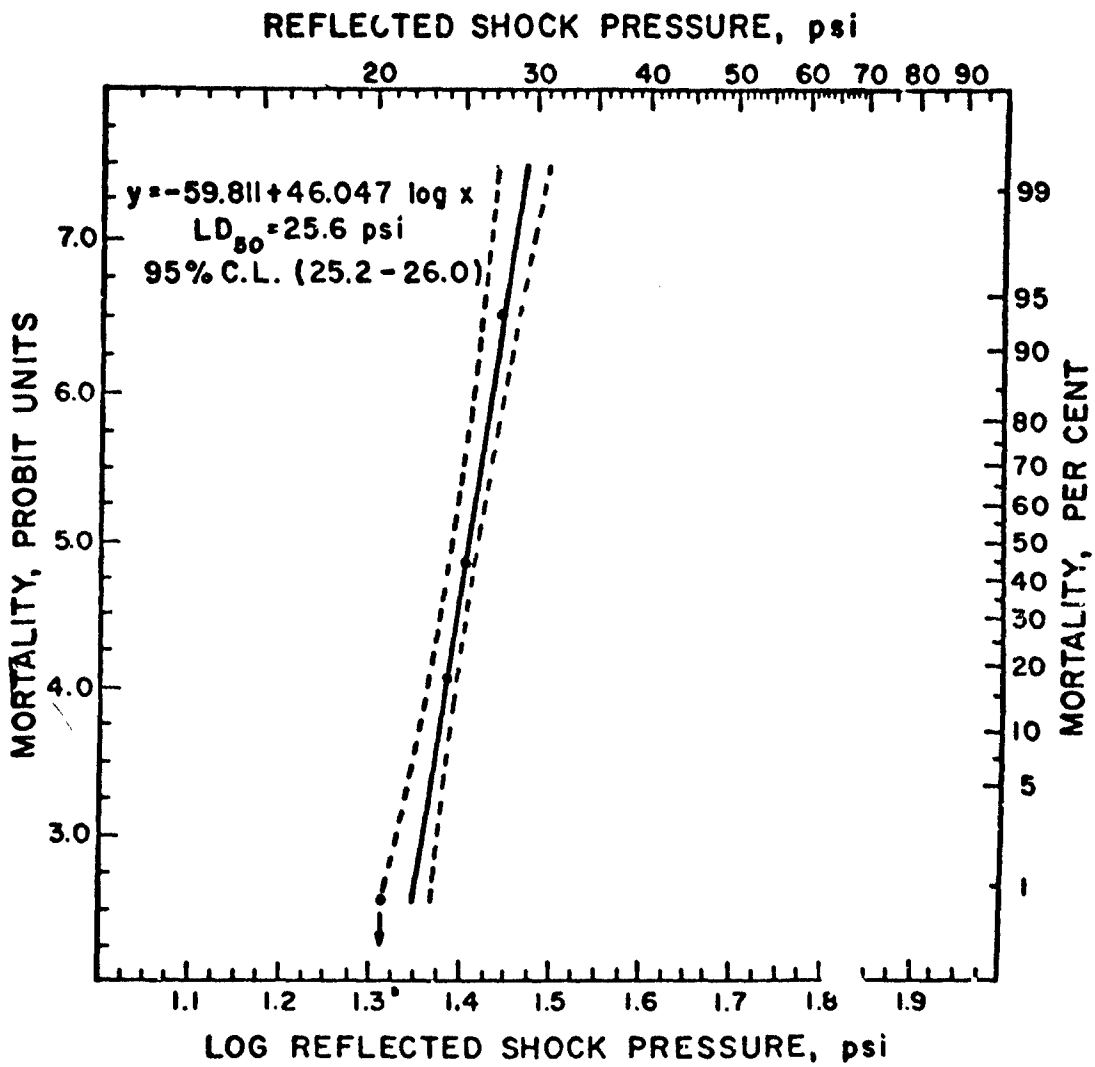

Figure 15. Probit Mortality Curve for Guinea Pigs Exposed to Reflected Pressures of 337-350-Msec Duration.

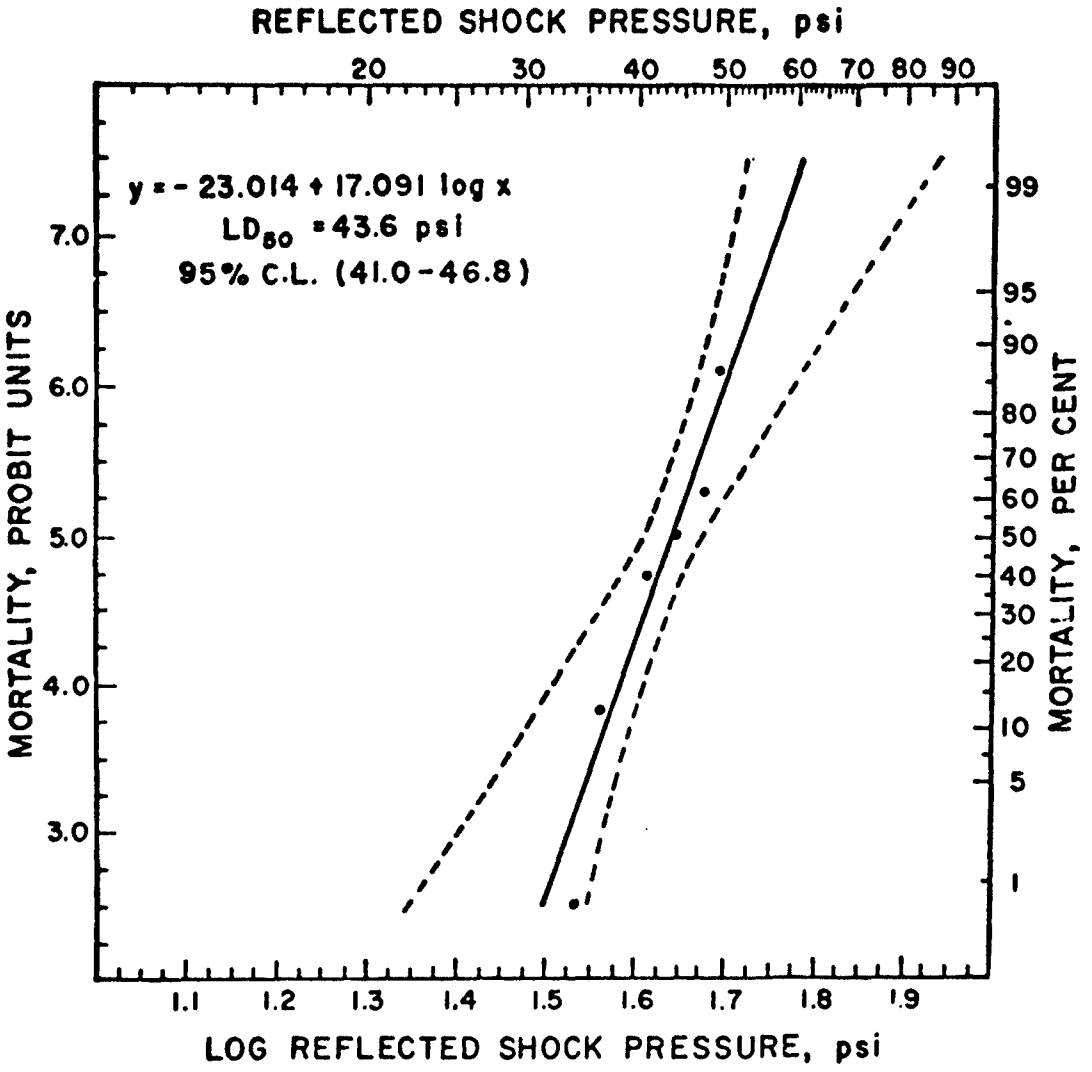

Figure 16. Probit Mortality Curve for Cats Exposed to Reflected Pressures of 358-380-Msec Duration.

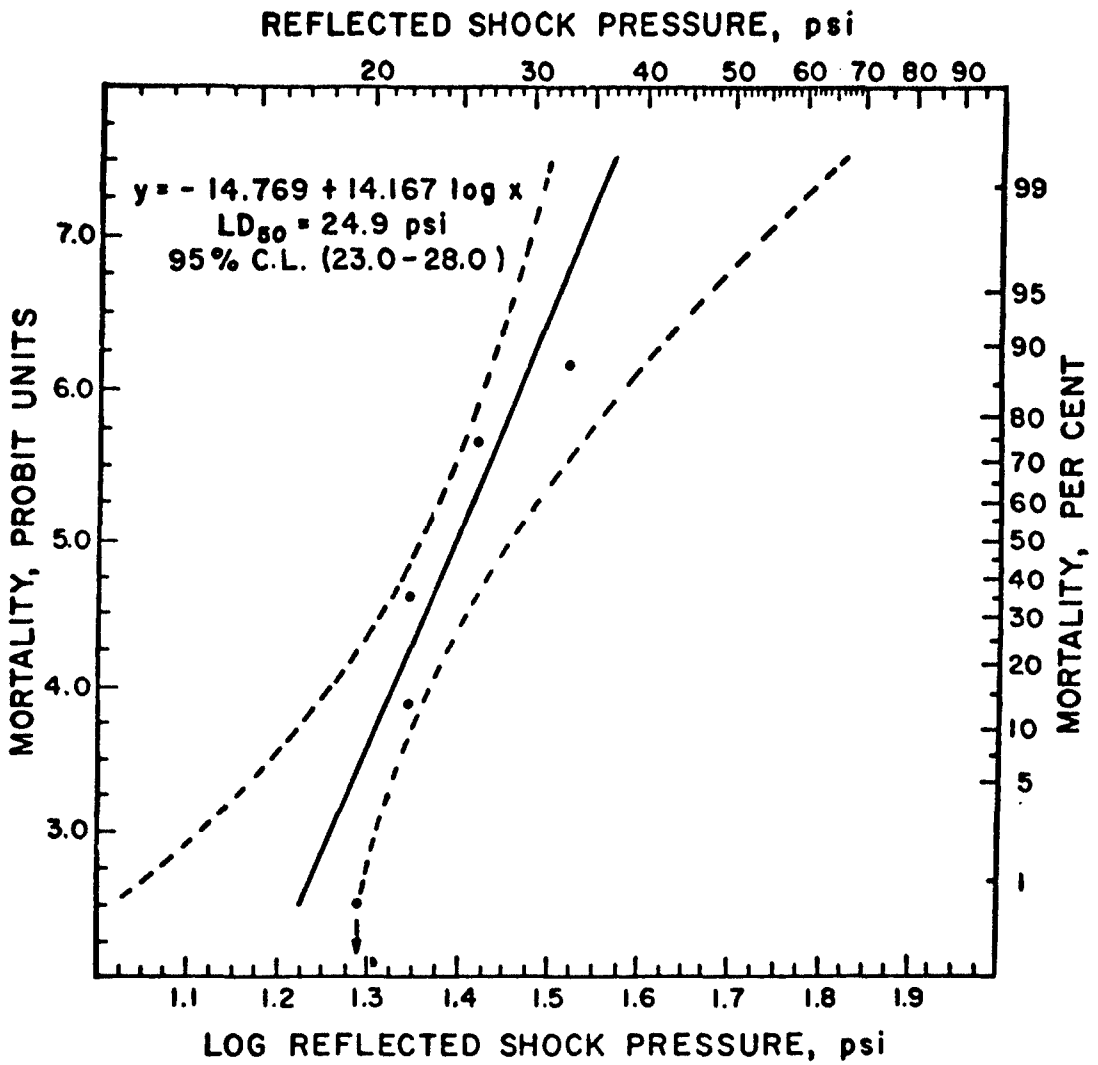

Figure 17. Probit Mortality Curve for Rabbits Exposed to Reflected Pressures of 339-364-Msec Duration.

are included on each curve and summarized in Table 7. The LD_{50}'s for the mice (26.4 psi), hamsters (28.6 psi), and rabbits (24.9 psi) were not significantly different at the 95-per cent confidence level – the rat's (30.6 psi) was above the other rodents with the cat's (43.6 psi) above that of the rat.

Gross Pathological Findings

The injuries found in small animals were of the same nature as those observed in the dogs and goats.

The mean lung weights for cats and hamsters, for the various pressure levels, are compared in Figures 18-19. Lung-weight data for mice, rats, guinea pigs, and rabbits have been previously reported.[11] The graphs show that the lung weight, except for high-pressure groups, generally increased with the dose and the survivors were below the nonsurvivors.

Most of the animals received eardrum ruptures indicating that the pressures, for the most part, in the lethal range to which they were exposed were far above that required for this injury – one hamster at the lowest dose level survived with eardrums intact. All cat eardrums were perforated.

DISCUSSION

Response for Dogs and Goats

The results of the present study show the resistance of dogs and goats to "fast"-rising overpressures increases markedly at the shorter pulse durations. The LD_{50} values increase by a factor of 4 or 5 from the longest to the shortest enduring blast wave. The region where the curves break (15-20 msec) has been termed the critical duration.[7] To the right of this critical time, biological response correlates with the peak reflected pressure; to the left, the reflected pressure impulse approaches the best fit to the data. It has been suggested that the critical duration is associated with the natural period of vibration of the system.[12] For durations which are "short" or "long" compared to the natural period, the results are governed by impulse or peak pressure, respectively.

According to Figure 20, a partial impulse criterion appears to fit the dog and goat results over the entire range of the pulse durations thus far studied. The partial impulse criterion takes into account only the initial portion of the pulse for a time that is related to the animal's size. By repeated trials a scaled time was found – $0.6m^{1/3}$ msec at Albuquerque altitude where m is the mass of the animal – which resulted in a near-constant, scaled partial impulse for the LD_{50} blast waves reported here; namely, 30 psi · $msec/kg^{1/3}$, on the average, as can be noted in Figure 20. For 16.5-kg dogs, an impulse of 76.4 psi · msec delivered over 1.53 msec corresponds to the median lethal dose; for 22.2-kg goats, the values were 8.42 psi · msec applied over the initial 1.69 msec of the pulse. Comparable

TABLE 7

RESULTS OF PROBIT ANALYSIS ON SMALL-ANIMAL 24-HOUR LETHALITY

Animal Species	Number of Animals	LD_{50}, psi	Probit Equation Constants	
			intercept, a	slope, b
Mice	200	26.4 (25.3-27.6)	-10.742	11.077±1.340
Hamsters	110	28.6 (27.5-29.7)	-21.133	17.933±3.060
Rats	150	30.6 (29.7-31.3)	-27.405	21.812±3.275
Guinea Pigs	120	25.6 (25.2-26.0)	-59.811	46.047±8.180
Cats	48	43.6 (41.0-46.8)	-23.014	17.091±4.420
Rabbits	40	24.9 (23.0-28.0)	-14.769	14.167±3.984

Note: Pressure Durations: 329-380 msec.

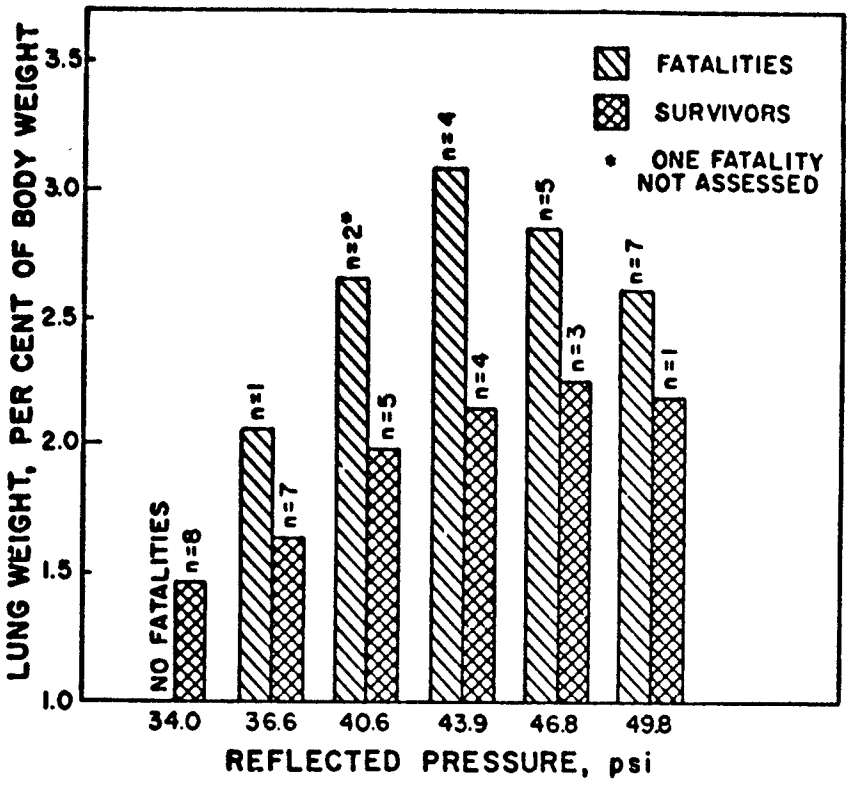

Figure 18. Lung Weight for Cats. Control Data for 10 Cats – Lung Weight, 0.75±0.04 (0.50-1.03) with Body Weight, 2.746 Kg (1.677-3.996).

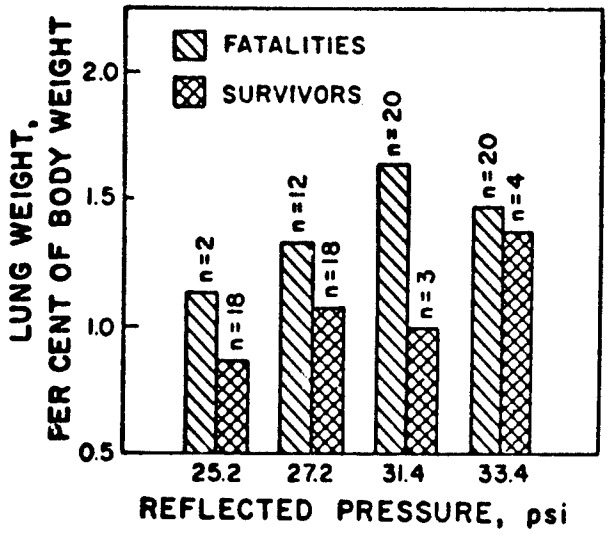

Figure 19. Lung Weight for Hamsters. Control Data for 25 Hamsters – Lung Weight, 0.56±0.02 (0.44-0.82) with Body Weight of 84.6 g (69-101).

Scaled Partial Impulse, $(I_o/m^{1/3})(12/P_o)^{1/2}$, of Reflected Blast Waves Resulting in 50% Mortality of 16.5-kg Dogs (o) and 22.2-kg Goats (□) Plotted as a Function of Scaled Duration $(t_+/m^{1/3})(P_o/12)^{1/2}$, where

I_o is overpressure impulse in psi-msec from arrival of blast wave to time t_o,
t_o is $0.6m^{1/3}(12/P_o)^{1/2}$ msec,
m is body mass of the animal in kg,
P_o is ambient pressure in psi, and
t_+ is duration of the blast wave in msec

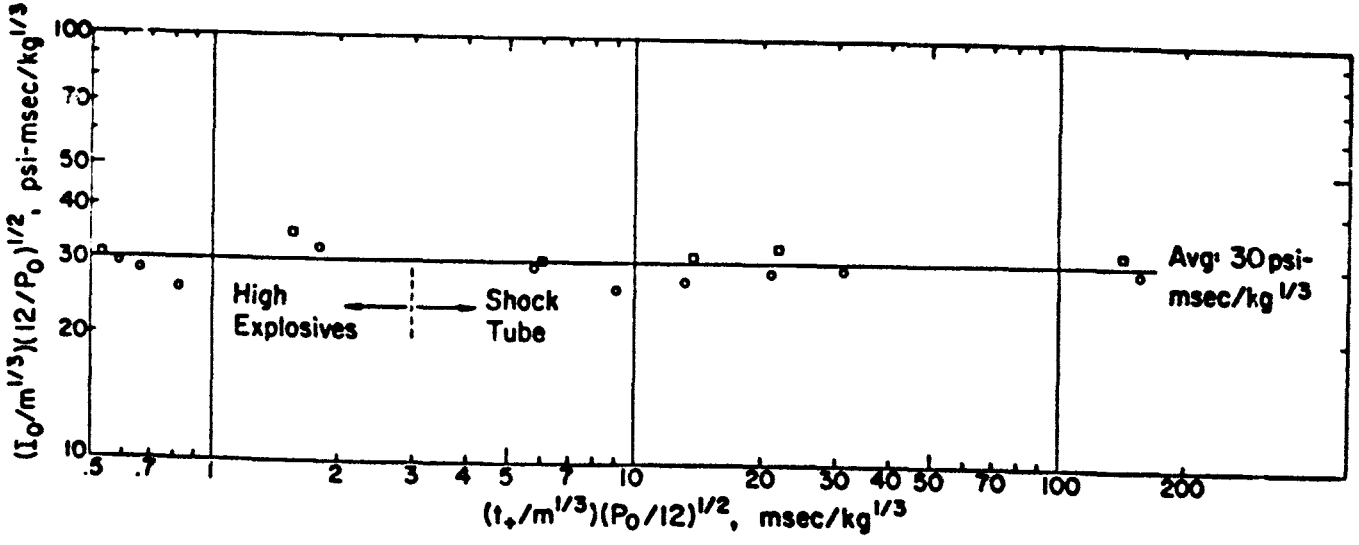

Figure 20. Partial Impulse of Reflected Blast Waves Resulting in 50-Per Cent Mortality.

figures for a 70-kg mammal would be 124 psi · msec delivered during the first 2.47-msec portion of the wave. The above data and those in Figure 20 apply to ambient pressures of 12.0 psia, but can be applied to other altitudes using the given scaling relations. Details of the derivations of these scaling methods have already been reported.[3]

Preliminary calculations show that the partial impulse criterion applies to recently obtained LD_{50} values for several other large species. That is, for 52-kg sheep, an LD_{50} on the order of 160 psi reflected pressure and about 3-msec duration was obtained with 64-lb charges detonated overhead as in the present study, and for 54-kg sheep (LD_{50} of 53 psi) and 180-kg cattle (LD_{50} of 43 psi) which were subjected to reflected pressures enduring for 212 and 184 msec, respectively, in a shock tube.[13] So far, this criterion has only been applied to blast waves that rise in a near-instantaneous manner. Further analyses should determine whether the partial impulse criterion related to blast waves that rise in two or more steps, as encountered close to reflecting surfaces where the incident and reflected shock fronts are applied to the target at different times.

In the present experiments, the subjects undoubtedly received the maximal reflected pressures for the corresponding incident shock front. Therefore, the reflected pressures were measured and considered to be the peak pressure in regard to their dose. Since in the shock tube with the end closed and on the concrete pad the flow associated with the incident shock wave is rapidly reversed by the reflection, there is little, if any, dynamic pressure involved. However, for animals exposed in the free-stream, results from full-scale tests indicate that the dynamic pressure and/or some fraction of the reflection from the animal itself apparently adds to the side-on pressure dose.[14] In this regard, the data given in Figure 21 for guinea pigs exposed in the freestream of a shock tube at different orientations to the incident shock front are pertinent.[15]

Figure 21, applying to LD_{50} conditions, shows the relation between different exposure positions and overpressures when the latter are expressed in terms of the incident, reflected, and dynamic pressures. The data are reasonably consistent and in fair agreement if the "effective" pressure or dose is chosen properly; viz., (a) the incident pressure plus the dynamic pressure for the guinea pigs exposed in either the vertical or prone, side-on positions;

(b) the incident pressure for prone exposures either head-on or tail-on to the advancing pulse, and

(c) the reflected pressure for animals mounted side-on against a reflecting surface.

Although this may be an oversimplification, these findings do suggest that the response data obtained for animals in the reflected-pressure geometry of this study can be transferred to the freestream situation by taking into account the dynamic pressure for broadside or upright targets. The results may be directly applied for targets oriented end-on; one qualification being that the waves are "sharp"-rising. As far as the partial-pressure-impulse criterion is concerned, the dynamic pressure impulse will be considered in subsequent analyses for targets exposed in the prone, broadside or vertical positions.

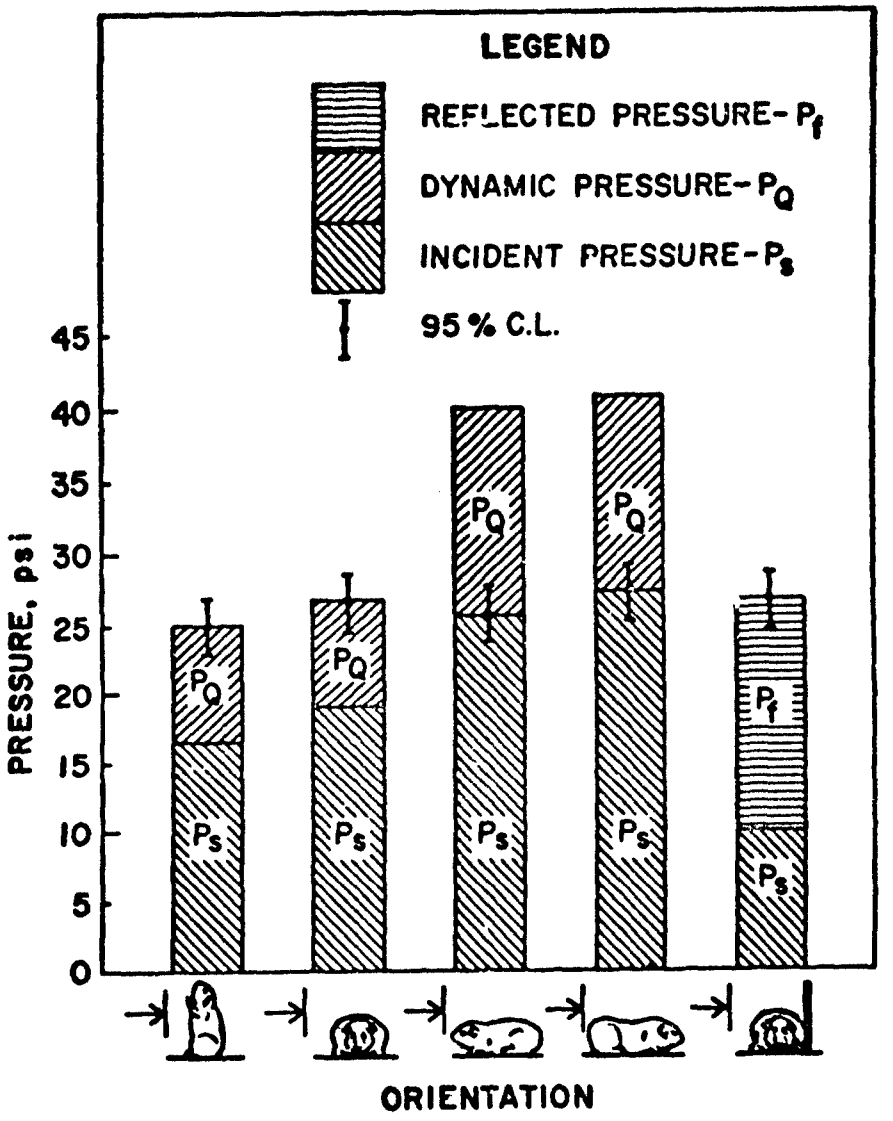

Figure 21. LD50 Conditions for Various Orientations of Guinea Pigs.

Threshold Lung Injury in Dogs

In these studies, the threshold for petechial lung hemorrhage in dogs was found to be at a mean reflected pressure of 13.5 psi (11.7-16.2) which was approximately 28 per cent of the LD_{50} value and generated by incident shock waves on the order of 5-6 psi. Petechial hemorrhages did not alter the respiratory and heart rates or cause significant histological changes in the lung tissue. Tests to relate respiratory-function impairment to comparable degrees of pulmonary injury are currently under way.

The threshold value for petechial hemorrhage for dogs in this study is near that for goats (10 psi side-on and 12 psi total pressure at a 230-msec duration). The latter were exposed side-on in the open 960 ft from a 500-ton explosion.[16] For blast waves of shorter durations, much higher pressures would be required to produce equivalent lung injury.

Response of Small Animals

Of the six small animal species tested in this study, the cat was found to be the most resistant to blast. The cat's LD_{50} was 43.6 psi—near that of the dog and goat. The only data in literature for cats give the lethal limit as 6 meters (19.8 ft) from a 50-kg charge (110 lb) from which one can calculate a pressure of 45 psi and from a 4-5-msec duration.[17] The orientation of the subjects was not stated.

As far as the other species are concerned, no information on hamsters has been reported in the literature for comparison. For the mice, rats, and rabbits, the values obtained in the present study were 4-5 psi below those previously reported for these animals exposed to "long"-duration pressures in the same shock tube, but in cages having less open area — 60 to 75 per cent compared to 90 per cent in the present study.[2] The value for guinea pigs was near 11 psi — lower than that previously found.

Interspecies Comparison

The results of this study indicate that, for "long"-duration blast waves, animal tolerance does not vary as greatly with respect to their sizes as it does with those enduring for short times. The LD_{50} for mice (26.4 psi) was less than that for goats (53.0 psi) by only a factor of two, and yet their body weights differed by several orders of magnitude. This relatively small interspecies difference strengthens existing estimates for man's response to long pulses.

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A series of three experiments were carried out. (1) A total of 204 dogs and 115 goats were exposed to shock-tube and high-explosive-produced reflected shock waves ranging in duration from 400 to 1.5 msec. LD_{50} values, calculated by probit analysis, showed similar patterns for both species, increasing at the shorter durations by a factor of 4 or 5 above those for long durations. (2) Sixty dogs were exposed in a shock tube to "sharp"-rising overpressures of near 400-msec duration at six-dose levels ranging from 9.2 to 35.8 psi. The degree of lung injury was graded and threshold for petechial hemorrhage determined. (3) Dose-response curves were compiled using data for 200 mice, 110 hamsters, 150 rats, 120 guinea pigs, 48 cats, and 40 rabbits exposed to "long"-duration reflected pressures in a shock tube. The tolerances (LD_{50}) for all six species are compared. Pathological observations for all species and lung-weight data for cats and hamsters are included.

Criteria for relating biological response to the various parameters of the blast wave are discussed.

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14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

Security Classification